Scheduling Deficit Wheat Irrigation with Data from an Evapotranspiration Network

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Abstract. *A two–year deficit irrigation study was conducted to determine the water use efficiency of winter wheat (*Triticum aestivum *L.) irrigated with fractions of crop evapotranspiration during the spring irrigation season. Fully irrigated treatments received sufficient irrigation to meet crop evapotranspiration, as calculated by a Penman–Monteith grass reference evapotranspiration equation and locally derived crop coefficients. Deficit irrigation treatments received 0%, 25%, 50%, or 75% of the fully irrigated amount on the same days. Irrigation was applied with a lateral move sprinkler system equipped with two LEPA methods (double–ended socks and bubblers) and two spray methods (above–canopy spray and overhead spray). All four sprinkler devices were spaced 1.52 m apart and located at the appropriate height for the sprinkler method. Cultural practices were similar to those used for high–yield wheat production in the southern Great Plains. Grain yields increased significantly with irrigation amount but not with sprinkler method. The full and 50% irrigation treatments averaged 7.00 and 6.32 Mg/ha for the two years. With 50% irrigation, seasonal water use efficiency averaged 0.95 kg/m^3, and spring irrigation water use efficiency averaged 1.70 kg/m^3, both being larger than for all other irrigation amounts. The winter wheat, deficit–irrigated with fractions of spring crop ET, efficiently utilized seasonal water consisting of irrigation, rainfall, and stored soil water over the entire 25% to 100% irrigation range. Spring irrigation was most efficiently applied at the 25% and 50% irrigation amounts. Deficit irrigation, as a fraction of spring ET, is well adapted to an irrigation water supply from low–producing wells and provides efficient water use over a range of both rainfall and irrigation amounts.*

Keywords. *Winter wheat, Deficit irrigation, Water use efficiency, Sprinkler irrigation, LEPA irrigation, Spray irrigation.*

Winter wheat can utilize water efficiently over a wide range of irrigation amounts (Musick and Porter, 1990; Musick et al., 1994), but reported relationships between seasonal evapotranspiration (ET) and yield or water use efficiency (WUE) vary. Musick et al. (1994) reported a linear regression slope of 1.22 kg/m^3 over a seasonal ET range of 208 to 800 mm. Similar linear relationships have been reported by Hanks and Rasmussen (1982) and Zhang and Orweis (1999), but Aggarwal et al. (1986) reported a curvilinear relationship between seasonal ET and yield. Musick et al. (1994) reported larger WUE with larger amounts of crop ET, but the regression coefficient relating WUE and yield was not significant. Zhang and Orweis (1999) also reported larger water use efficiency at higher yield levels, but Aggarawal et al. (1986) found that WUE decreased with crop ET. The relationship between ET and crop yield or WUE has practical implications for deficit irrigation scheduling. Deficit irrigation can be concentrated during critical stages of plant growth or applied to meet a fraction of full ET during the growing season.

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Critical growth stages for irrigating winter wheat generally occur from early spring growth to early grain development. Schneider et al. (1969) evaluated spring irrigation by applying all combinations of one through four 100–mm irrigations at early spring growth, booting, heading, and early grain development. The water use efficiency of spring irrigation increased with plant development from booting until heading and then decreased as the wheat approached maturity. Zhang et al. (1999) related relative yield to relative ET deficit for winter wheat receiving both fall and spring irrigations in the North China Plain. The most sensitive growth stages for preventing water stress were from stem elongation to heading and from heading to grain milk stage. Grain yields of irrigated wheat ranged from 3.01 to 5.25 Mg/ha, and seasonal WUE ranged from 1.20 to 1.40 kg/m^3 (Zhang et al., 1999). Dusek and Musick (1992) recommended adequate irrigation during boot stage through anthesis to increase grain number per square meter, the yield component most sensitive to water stress.

Deficit winter wheat irrigation can also be scheduled by applying a fraction of calculated ET throughout the spring or delaying irrigation until the soil water potential is lower than recommended. English and Nakamura (1989) estimated winter wheat ET from Penman reference ET and a crop coefficient and applied high– and low–frequency irrigation at 20% increments of estimated ET. The linear relationship of ET to yield was highly significant, but irrigation frequency did not significantly affect yields. Jensen and Sletten (1965) scheduled winter wheat irrigation according to the water potential of Pullman clay loam soil and obtained the highest 3-year average yield of 2.96 Mg/ha with a soil water potential of –0.4 MPa. Schneider and Howell (1997) compared irrigating winter wheat at 0%, 33%, 67%, and 100% of full soil water replenishment with full irrigation either delayed in the spring or terminated early. When compared with delayed or early-terminated full irrigation, continuous deficit irrigation generally resulted in larger WUE with the 33% and 67% irrigation amounts and larger yields with the 67% irrigation amount.

Irrigating winter wheat with fractions of ET is especially well suited to a limited irrigation water supply from low-producing wells. Planting and emergence irrigating can be staggered over an interval of a month or more, and water use during the winter is usually low. During the spring when crop ET exceeds the capacity of wells, irrigating with a fraction of the ET can still result in highly efficient irrigation water use.

The objective of this study was to evaluate deficit winter wheat irrigation in 25% increments of the amount required to fully meet ET calculated by the North Plains (of Texas) Evapotranspiration Network (Howell et al., 1998).

Procedure

The study was conducted at the USDA Conservation and Production Research Laboratory at Bushland, Texas (35° 11′ N lat., 102° 06′ W long., 1170 m msl elevation) during the 1997–98 and 1998–99 winter wheat seasons. The Pullman clay loam at the research site is a fine, mixed, superactive, Thermic torrertic Paleustoll with a dense B21t subsoil from about the 0.15 to 0.40 m depths and a calcic horizon starting at about the 1.5 m depth. For the upper 1.0 m soil profile, Unger and Pringle (1981) measured 139 mm of available soil water capacity between the –0.033 and –1.5 MPa matric potentials. Soil samples collected beneath the Pullman soil profile contained less than 600 mm of deep percolation after 20 years of furrow irrigation (Aronovici and Schneider, 1972), and deep percolation of sprinkler-irrigated water is believed to be small. The slope of the 1.8 ha research field was uniform at about 0.25% in the direction of movement of the lateral move irrigation system and 0.22% perpendicular to the movement of the system.

Experimental Design

Two low-energy precision application (LEPA) and two spray sprinkler methods were evaluated with five irrigation amount treatments. Double-ended LEPA socks (Fangmeier et al., 1990) were dragged through alternate furrows with both discharge ends on the ground. LEPA bubblers (New and Fipps, 1990) were located about 0.3 m above the soil surface. Above-canopy spray heads were positioned just above the mature height of the wheat (1.0 m), and overhead spray heads were positioned at a height of about 1.5 m. The irrigation control treatment, I_{100}, received sufficient 25-mm spring irrigations to meet the full crop ET calculated by the North Plains (of Texas) Evapotranspiration Network (Howell et al., 1998). Estimated evapotranspiration was the product of reference ET calculated by a Penman-Monteith grass reference ET (Howell et al., 2000) equation and locally derived crop coefficients. On the same day, deficit spring irrigation treatments, designated as I_{75}, I_{50}, I_{25}, and I_0, received the percent of the I_{100} irrigation denoted by the subscript. Field plots were arranged in a split-split plot design with sprinkler amounts blocked across each span of a 3-span lateral-move irrigation system and sprinkler methods randomized under each span. Plots were 9 m wide (perpendicular to movement of the irrigation system) by 25 m long (in the direction of movement of the irrigation system).

Gravimetric soil water measurements provided data for calculating growing season soil water depletion, and neutron soil water measurements in the I_{100} and I_{50} irrigation treatments verified the accuracy of the irrigation scheduling water balance. One gravimetric soil water sample per plot was collected in 0.30-m increments to the 1.8-m depth both just after planting and immediately after harvest. About every four weeks during the spring irrigation season, neutron soil water measurements were made in each I_{50} and I_{100} plot in 0.20-m increments to the 2.4-m depth. These measurements were made with a locally field-calibrated CPN Model 503DR (Campbell Pacific Nuclear, Martinez, Cal.) neutron moisture meter (Evett and Steiner, 1995).

Irrigation Equipment

Irrigations were applied with a hose-fed Valmont Model 6000 (Valmont Industries, Inc., Valmont, Neb.) lateral-move irrigation system equipped with a computer-aided management system (CAMS) controller. The lateral-move system had three 39-m long spans with twenty-four 1.52-m spaced sprinkler drops under each span. Groundwater was pumped from the Ogallala aquifer, temporarily stored in a surface reservoir, and then pumped to the irrigation system through a 114-mm diameter hose at 22.8 L/s. Senninger Super Spray heads (Senninger Irrigation, Inc., Orlando, Fla.) were used to meter the flow into the double-ended LEPA drag socks (Quest and Sons, Lubbock, Texas). Senninger Quad IV spray heads were used in the LEPA mode for the LEPA bubble application and in the irrigate mode for the above-canopy spray application. The overhead spray treatment was applied with Senninger LDN (low-drift nozzle) spray heads fitted with a flat upper spray plate and a convex lower spray plate each having 36 grooves. All sprinkler devices were spaced 1.52-m apart, equipped with 5.6 mm nozzles and 69 kPa pressure regulators, and discharged 19.0 L/min. The irrigation amount was controlled by varying the speed of the irrigation system, and the sum of the individual nozzle discharges was measured with a propeller meter.

Cultural Practice

Cultural practices were similar to those used by southern Great Plains growers for high-yield irrigated winter wheat. Both wheat crops were grown on land that had been fallowed during the previous year to store precipitation and reduce insect, disease, and weed populations. Table 1 lists fertilizer rates, herbicide applied, dates of planting and harvesting, seeding rate, and dates of the first and last spring irrigations. Tandem disking was used for primary tillage, and sweep tillage was used for preplant weed control and seedbed preparation. Ogallala variety wheat (*Triticum aestivum* L.) was flat planted with a 6.1-m wide, Tye grain drill in 0.1-m spaced rows running perpendicular to the movement of the lateral-move irrigation system.

Table 1. Agronomic and irrigation data for the two winter wheat crops.

Variable	1997–1998	1998–1999
Fertilizer	123 kg (N)/ha preplant 36 kg (N)/ha with irrigation[a] 112 kg (P)/ha preplant	140 kg (N)/ha preplant 40 kg (N)/ha with irrigation[a] 112 kg (P)/ha preplant
Herbicide applied	None	2,4–D
Planting date	2 Oct 1997	29 Sept 1998
Seeding rate	67 kg/ha	67 kg/ha
Harvest date	24 June 1998	29 June 1999
Preplant irrigations	None	8 Sept 1998 – 25 mm 10 Sept 1998 – 25 mm
Emergence irrigations	10 Oct 1997 – 25 mm	30 Sept 1998 – 25 mm 1 Oct 1998 – 13 mm 10 Oct 1998 – 10 mm
Winter irrigation	7 Nov 1997 – 25 mm	15 Jan 1999 - 27 mm.
First spring irrigation	3 April 1998	9 March 1999
Last spring irrigation	2 June 1998	24 May 1999
I_{25} spring irrigation amount	109 mm	73 mm
I_{50} spring irrigation amount	213 mm	144 mm
I_{75} spring irrigation amount	319 mm	221 mm
I_{100} spring irrigation amount	419 mm	297 mm

[a] For deficit irrigation, this nitrogen was applied in proportion to the irrigation amount.

Preplant, emergence, and winter irrigations were applied with Senninger Super spray heads to wet the entire soil surface for seed germination and later for nodal root development. All spring irrigations were applied with the two LEPA and two spray sprinkler methods. Irrigation treatment plots were separated by dikes to prevent runoff from wetter plots onto drier ones, and sprinkler method plots were separated by small ditches to prevent any runoff from LEPA plots onto spray plots.

Grain yield was measured both by combine harvesting and by hand sampling 1–m^2 areas in each plot. A Hege (Hege Equipment, Inc., Colwick, Kansas) plot combine with a 1.52–m wide header was used to harvest one full length of each plot. The entire above–ground biomass was collected from the 1–m^2 areas, oven dried at 70°C, and weighed to determine total dry matter. The dry matter samples were then threshed with the Hege combine, and seed mass was measured to determine grain yield and calculate harvest index. Individual seed mass was determined from two 500–grain subsamples. Grain yields were adjusted to 13% water content on a wet weight basis, and water use efficiencies were calculated from those yields. WUE was defined as grain yield divided by seasonal water use. Seasonal water use was calculated as the sum of total rainfall and seasonal soil water depletion plus emergence, winter, and spring irrigations. IWUE was calculated as the treatment grain yield minus the average I_0 grain yield divided by the spring irrigation amount. Data were analyzed with a general linearized model for split–split plot designs (SAS Institute, Inc., Cary, N.C.)

Results

Rainfall and Irrigation

Cumulative rainfall and irrigation during the two wheat seasons are illustrated in figure 1 along with the average, cumulative 50–year rainfall, which totals 218 mm from 1 October to 30 May. For the 1998 crop, 228 mm of precipitation was uniformly distributed over the growing season. In 1999, precipitation over the growing season totaled 497 mm, but 318 mm occurred in October and May.

Spring irrigation complemented the rainfall to meet the ET requirements of the winter wheat (fig. 1). In 1998, 419 mm of spring irrigation was applied to the I_{100} treatments in 16 irrigations beginning on 3 April and ending on 2 June. In 1999, eleven spring irrigations were applied to the I_{100} treatments from 9 March to 24 May with the cumulative amount being 297 mm. Total spring irrigation for the deficit–irrigated treatments is listed in table 1. The table also lists preplant and emergence irrigations applied to all irrigation treatment plots to ensure seed germination and seedling emergence. The 1997–98 crop required only an emergence irrigation and an early winter irrigation. With a summer drought causing a very dry upper soil profile in the fall of 1998, the 1998–99 crop required both preplant and emergence irrigations in addition to one winter irrigation.

Soil Water

Early season soil water content was high and uniform across all treatments and replicates following fallow season storage of rainfall for both years and preplant irrigation during September 1998. For the Pullman clay loam soil, a lower limit for maximum wheat yields is about 50% of plant available soil water soil (Musick et al., 1994) or about 460 mm total soil water in the 1.8–m profile. On 12 October 1997, the average 1.8–m profile soil water storage for the 60 plots was 545 mm, and treatment or replicate averages ranged from 539 to 554 mm. On 19 October 1998, the 1.8–m profile soil water averaged 573 mm, and treatment or replicate averages ranged from 560 to 592 mm. The large amount of soil water at planting–time provided the opportunity for large amounts of seasonal soil water depletion by both crops. In 1998, seasonal soil water depletion ranged from 143 mm on the I_{100} treatments to 170 mm on the I_0 treatments (table 2).

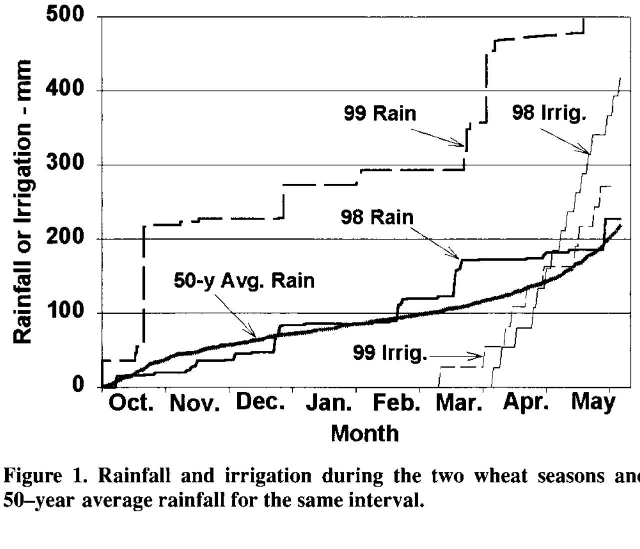

Figure 1. Rainfall and irrigation during the two wheat seasons and 50–year average rainfall for the same interval.

Table 2. Grain yield, seasonal soil water depletion, ET, water use efficiencies, seed mass, and harvest index for 1998. Averages followed by the same letter are not significantly different ($p < 0.05$).

Irrigation amount	Sprinkler method	Grain yield (Mg/ha)	Soil water depletion (mm)	ET[a] (mm)	WUE (kg/m^3)	IWUE (kg/m^3)	Seed mass (mg/kernel)	Harvest index
0%	—	2.46	170	432	0.57	—	29.6	0.21
25%	LEPA sock	4.59	162	533	0.87	2.10	30.1	0.25
	LEPA bubble	4.67	171	542	0.86	1.93	30.6	0.26
	Above–canopy spray	4.27	143	513	0.83	1.78	30.5	0.25
	Overhead spray	4.40	150	521	0.85	1.91	29.5	0.26
50%	LEPA sock	6.66	148	622	1.07	2.08	31.4	0.29
	LEPA bubble	7.36	169	644	1.14	2.36	29.7	0.28
	Above–canopy spray	6.65	174	648	1.03	2.07	31.4	0.30
	Overhead spray	6.48	162	637	1.02	1.99	29.8	0.28
75%	LEPA sock	6.92	164	745	0.93	1.46	29.9	0.28
	LEPA bubble	6.58	164	745	0.88	1.35	31.9	0.29
	Above–canopy spray	6.28	182	763	0.82	1.25	30.2	0.26
	Overhead spray	5.94	148	729	0.82	1.14	32.0	0.26
100%	LEPA sock	7.52	174	855	0.88	1.25	30.9	0.30
	LEPA bubble	6.99	137	818	0.86	1.22	29.3	0.29
	Above–canopy spray	7.26	126	807	0.90	1.18	30.1	0.30
	Overhead spray	6.92	134	815	0.85	1.10	31.2	0.29
Irrigation amount averages								
0%	—	2.46d	170	432	0.57c	—	29.6c	0.16d
25%	—	4.48c	157	527	0.85b	1.93a	30.2a	0.25c
50%	—	6.79b	163	638	1.06a	2.13a	30.6a	0.29a
75%	—	6.43b	164	745	0.86b	1.30b	31.0ab	0.27b
100%	—	7.17 a	143	824	0.87b	1.19b	30.4a	0.29a
Sprinkler method averages								
—	LEPA sock	5.63a	165	639	0.86a	1.72a	30.4	0.25
—	LEPA bubble	5.63a	159	633	0.87a	1.71a	30.0	0.26
—	Above–canopy spray	5.36b	159	633	0.82b	1.57b	30.3	0.25
—	Overhead spray	5.24b	155	629	0.82b	1.54b	30.7	0.26
	Yearly averages	5.47	160	633	0.84	1.64	30.3	0.25

[a] Includes 212 mm of growing season precipitation.

In 1999, seasonal depletion ranged from 153 mm on the I_{75} treatments, to 120 mm on the I_{100} treatment (table 3).

Monthly neutron soil water measurements during the spring of 1998 (fig. 2) illustrate that soil water for the I_{50} and I_{100} treatments was similar until after the 9 April 1998 sampling. Up to this date, soil water in the 0.3 to 1.3 m profile of the I_{50} irrigation treatment remained in the 0.30 to 0.35 volumetric fraction range, and this was sufficient to produce grain yields similar to those of the I_{75} and I_{100} irrigation treatments. Similar data are not available for the spring of 1999 because of a malfunction in a neutron soil water meter that was not discovered until late May.

Grain Yield and Yield Components

Grain yields measured by combine harvesting are listed in tables 2 and 3 for individual treatments and for irrigation amount, sprinkler method, and yearly averages. Grain yields increased significantly with irrigation amount, but the distribution of the increases varied between the two years. In 1998, the yields increased significantly from I_0 to I_{25} to I_{50} or I_{75}, and then increased significantly from I_{50} or I_{75} to I_{100}. That year, lodging limited the yield on the spray–irrigated I_{75} and I_{100} treatment plots, and the I_{50} average yields exceed those of I_{75}. In 1999, the grain yields increased significantly with each irrigation increment. In 1998, yields from the LEPA plots were significantly larger than those from the spray plots due to the lodging on the spray–irrigated I_{75} and I_{100} plots. In 1999, yields did not vary significantly among the irrigation method averages. Yearly average yields were not significantly different for the two crops.

Variations in seed mass among the irrigation amounts were small, but there was one significant difference each year. In 1998, average seed mass for I_{75} was significantly larger than the average for I_0, and in 1999, seed mass for I_{100} was significantly larger than for I_{50}. We believe the smaller seed mass for I_{50} is due to sampling error rather than to a treatment effect. Differences in seed mass due to sprinkler method were not statistically significant either year, but the 1998 average seed mass was significantly larger than the 1999 average ($p \leq 0.0023$). A regression analysis of seed mass vs. seasonal water use similar to that of Dusek and Musick (1992) resulted in insignificant regression coefficients both years. The small ranges of seed mass in comparison to large ranges in grain yields illustrates that seed number per unit land area rather than seed mass was the major yield component.

Harvest index (H.I.), the grain fraction of total above–ground biomass, increased significantly with irrigation amount for both years. In 1998, there was a significant increase in H.I. from I_0 to I_{25} and a further significant increase to I_{75}. The H.I. values for I_{100} and I_{50} were then significantly larger than for the other three irrigation amounts. In 1999,

Table 3. Grain yield, seasonal soil water depletion, ET, water use efficiencies, seed mass, and harvest index for 1999. Averages followed by the same letter are not significantly different ($p \leq 0.05$).

Irrigation amount	Sprinkler method	Grain yield (Mg/ha)	Soil water depletion (mm)	ET[a] (mm)	WUE (kg/m^3)	IWUE (kg/m^3)	Seed mass (mg/kernel)	Harvest index
0%	—	4.08	148	557	0.73	—	29.3	0.28
25%	LEPA sock	4.95	143	624	0.80	1.20	30.1	0.30
	LEPA bubble	4.87	126	607	0.81	1.56	29.9	0.29
	Above–canopy spray	4.86	149	630	0.78	1.39	29.9	0.29
	Overhead spray	5.01	146	627	0.80	1.29	29.9	0.30
50%	LEPA sock	6.01	160	712	0.84	1.34	28.2	0.30
	LEPA bubble	5.91	130	682	0.87	1.27	30.3	0.30
	Above–canopy spray	5.45	144	696	0.78	1.06	29.4	0.30
	Overhead spray	6.02	145	697	0.86	1.35	28.0	0.30
75%	LEPA sock	6.53	141	770	0.85	1.11	29.5	0.32
	LEPA bubble	6.03	151	780	0.78	0.89	29.9	0.32
	Above–canopy spray	6.15	160	789	0.78	0.94	30.1	0.32
	Overhead spray	6.47	159	788	0.82	1.08	30.3	0.30
100%	LEPA sock	6.86	132	838	0.82	0.94	30.6	0.32
	LEPA bubble	7.09	106	812	0.87	0.90	29.8	0.33
	Above–canopy spray	6.63	131	836	0.79	0.86	30.4	0.33
	Overhead spray	6.57	109	814	0.81	0.84	30.5	0.31
Irrigation amount averages								
0%	—	4.08e	148	557	0.73b	—	29.3ab	0.28c
25%	—	4.93d	141	622	0.80a	1.36a	29.9ab	0.29b
50%	—	5.85c	145	697	0.84a	1.26a	29.0b	0.30ab
75%	—	6.30b	153	782	0.81a	1.01b	29.9ab	0.31a
100%	—	6.79a	120	825	0.82a	0.88b	30.3a	0.32a
Sprinkler method averages								
—	LEPA sock	5.69	144	700	0.81	1.15	29.5	0.30
—	LEPA bubble	5.60	133	688	0.81	1.16	29.8	0.30
—	Above–canopy spray	5.43	146	701	0.77	1.06	29.8	0.30
—	Overhead spray	5.63	142	697	0.80	1.14	29.6	0.30
Yearly averages		5.57	141	697	0.80	1.13	29.7	0.30

[a] Includes 334 mm of growing season precipitation.

H.I. values for I_{100} and I_{75} were significantly larger than the other irrigation amounts, and H.I. for I_0 was again significantly less than for the spring–irrigated treatments. Regression of H.I. vs. seasonal water use resulted in significant regression coefficients ($p \leq 0.05$) both years with $r^2 = 0.657$ in 1998 and $r^2 = 0.891$ in 1999. H.I. did not vary significantly with sprinkler method either year, but average H.I. in 1999 was significantly larger than that in 1998 ($p \leq 0.0001$).

Water Use Efficiency

The range of WUE for the irrigation treatments was small over the I_{25} to I_{100} range except for I_{50} in 1998. That year, soil water and weather conditions made I_{50} an exceptionally efficient irrigation amount, and this will be discussed in more detail later. Even though the range was small, WUE varied significantly among the irrigation amounts (tables 2 and 3). In 1998, WUE was significantly larger for I_{50} than for the other irrigation amounts and significantly smaller for I_0 than for the four larger irrigation amounts. In 1999, WUE values for all four spring–irrigated treatments were larger than for I_0. WUE was larger in 1998 for the LEPA sprinkler methods than for the spray methods, but in 1999 it did not vary significantly among the four sprinkler methods. Yearly average WUE did not vary significantly between the two years.

During both years, water use efficiency of spring irrigation (IWUE) was significantly larger for I_{25} and I_{50} than for the two larger irrigation amounts. With the large I_0 grain yield of 4.08 Mg/ha in 1999, all spring irrigation water use efficiencies were small in comparison to the corresponding values for 1998. In 1998, IWUE was larger for the LEPA sprinkler methods than the spray methods, but in 1999 it did not vary significantly among the four sprinkler methods. Yearly average IWUE was significantly larger in 1998 than in 1999 ($p \leq 0.0001$).

Seasonal Water Use

Seasonal water use for the irrigation amount treatments ranged from 432 to 824 mm in 1998 and from 557 to 825 mm in 1999. Both maximum values are within the 791 to 957 mm ET range measured over three years by Howell et al. (1995) at Bushland. Seasonal water use increased incrementally with percent irrigation, but the increments decreased slightly for the larger irrigation amounts due to reduced seasonal soil water depletion. During both years, average seasonal water use by the four sprinkler methods was essentially equal.

Seasonal water use during 1998 and 1999 for all treatments is plotted vs. grain yield in figure 3. The linear regression coefficient of 0.0103 Mg/mm (1.03 kg/m^3) is similar to that derived by Musick et al. (1994) for the southern

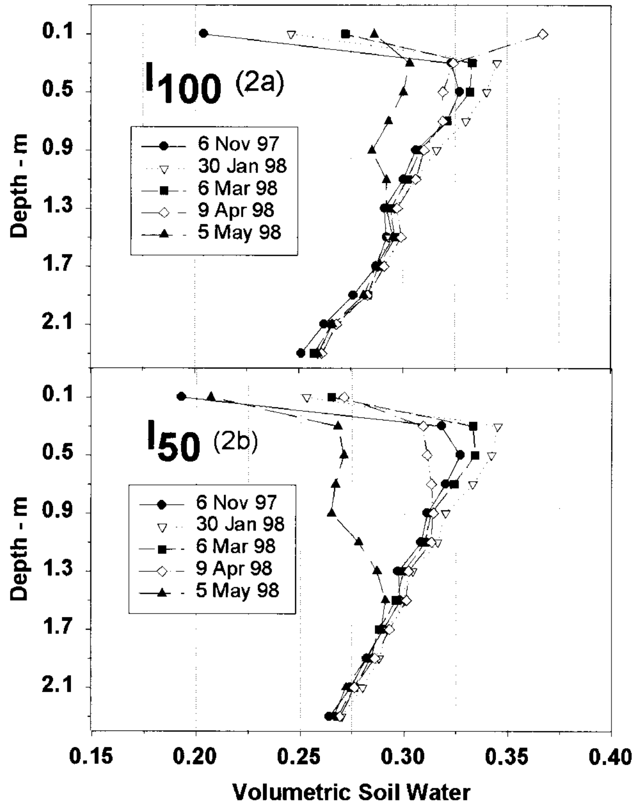

Figure 2. Average soil water contents for I_{100} and I_{50} during the spring of 1998.

Great Plains. The only data points poorly estimated by the regression equation are those for the I_{50} treatments in 1998. With the four I_{50} treatments deleted from the analysis, the regression coefficient remains essentially equal at 0.0106 Mg/mm, but the r^2 value increases to 0.939. Possible reasons for the larger than expected I_{50} yields are provided in the Discussion section.

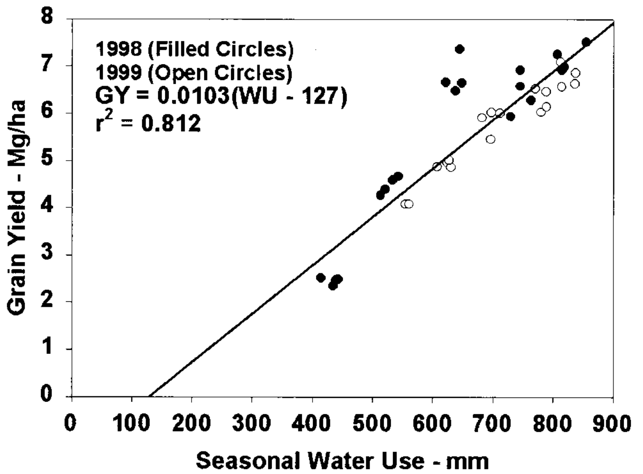

Figure 3. Regression of seasonal water use vs. grain yield for the 1998 and 1999 crop years.

Discussion

Deficit irrigation with fractions of ET resulted in efficient use of seasonal rainfall, stored soil water from preseason rainfall, and irrigation water. The range of WUE was small for the four spring irrigation amounts, and IWUE was largest with 25% and 50% irrigation amounts. With a continuously available, but deficit, water supply, applying fractions of full ET is easier to schedule than large irrigations at critical growth stages. Applying fractions of full ET also precludes the application of large irrigations before large rainfall events. Schneider and Howell (1997) compared irrigating to supply fractions of soil water replenishment with delayed full irrigation or full irrigation with an early cutoff date. The fractional soil water replenishment generally resulted in both larger WUE and IWUE. If irrigation water for winter wheat is continuously available on demand, but in deficit amounts, applying the water to meet fractions of spring ET with sprinkler systems is likely to be more efficient than applying large, critically timed irrigations.

The highly efficient I_{50} deficit irrigation in 1998 is believed to be due to the large amounts of stored soil water and spring air temperatures that were favorable for winter wheat. After 15 March, minimum temperatures were never more than 1°C to 2°C below freezing, and maximum temperatures until 15 May were below 32°C. Large amounts of stored soil water and timely rainfall in February and March combined with moderate ET rates resulted in only small amounts of soil water depletion for the I_{50} irrigation treatment. The data in figures 2a and 2b illustrate that soil water for I_{50} and I_{100} was essentially equal until 9 April 1998. The vigorously growing crop then depleted large amounts of stored soil water, as illustrated by the I_{50} soil water data for 5 May 1998.

Grain yields and water use efficiency were significantly larger with LEPA than with spray irrigation in 1998 but not in 1999. The reduced yields with 75% and 100% spray irrigation in 1998 were caused more by lost grain during harvest than by reduced grain filling. For spray irrigation with 75% and 100% irrigation, the hand–harvested 1–m^2 yields were 0.18 and 1.19 Mg/ha larger, respectively, than the combine–harvested yields. In addition, the nearly equal seed masses and harvest indexes across the sprinkler methods illustrate that the grain was equally developed. The equal yields and water use efficiencies with the LEPA and spray sprinkler methods in 1999 are similar to results by Schneider and Howell (1997), but maximum grain yields in this study were larger. During most years, the LEPA and spray sprinkler methods are likely to be equally efficient for irrigating winter wheat.

On–farm deficit irrigation is ultimately a management decision based on variables such as commodity prices, water costs, energy costs, irrigation system costs, allowable risk, and irrigation preference (English and Nuss, 1983). The production function in figure 3 is a guideline for the return on irrigation water in the southern Great Plains. Each 10 m^3 (hectare–millimeter) of applied water increased the grain yield 0.0103 Mg/ha, and an average 25–mm (1–inch) center pivot irrigation would return 0.258 Mg/ha (9.46 bushels/acre) of grain. With commodity prices of $110 per megagram ($3.00 per bushel), the gross income on a 25–mm irrigation would be $28.38 per hectare ($11.49 per acre). For other wheat prices, the gross profit for a 25–mm irrigation can be increased or decreased in proportion to the wheat price.

Conclusions

Winter wheat efficiently utilized irrigation water applied during the spring as fractions of that needed to provide full ET. Grain yields with the I_{50} irrigation amount were 95% and 86% as large as with the I_{100} amount over the two respective years. WUE was largest with I_{50}, and IWUE was largest with either I_{25} or I_{50}. In the Southern Great Plains, continuously providing 25% or more of the irrigation water requirement for winter wheat will normally ensure efficient use of both irrigation and rainfall.

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